

Suzaku Observations of AWM 7 Cluster of Galaxies: Temperature, Abundance and Bulk Motions

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(Received —; accepted —)

Abstract

We carried out 3 observations of the cluster of galaxies AWM 7, for the central region and 20'-east and 20'-west offset regions, with Suzaku. Temperature and abundance profiles are measured out to $27' \simeq 570 h_{70}^{-1}$ kpc, which corresponded to $\sim 0.35 r_{180}$. The temperature of the intra-cluster medium (ICM) slightly decreases from 3.8 keV at the center to 3.4 keV in $\sim 0.35 r_{180}$ region, indicating a flatter profile than those in other nearby clusters. Abundance ratio of Si to Fe is almost constant in our observation, while Mg to Fe ratio increases with radius from the cluster center. O to Fe ratio in the west region shows increase with radius, while that in the east region is almost flat, though the errors are relatively large. These features suggest that the enrichment process is significantly different between products of type II supernovae (O and Mg) and those by type Ia supernovae (Si and Fe). We also examined positional shift of the central energy of He-like Fe-K α line, in search of possible rotation of the ICM. The 90% upper limit for the line-of-sight velocity difference was derived to be $\Delta v \lesssim 2000 \text{ km s}^{-1}$, suggesting that the ellipticity of AWM 7 is rather caused by a recent directional infall of the gas along the large-scale filament.

Key words: galaxies: clusters: individual (AWM 7)

1. Introduction

Mass profile of the cluster, which is a useful parameter in constraining the cosmology, is determined through X-ray measurements of the temperature and density structure of the ICM under the assumption of hydrostatic equilibrium of the ICM. Recent observations showed spatially resolved spectra of clusters with good spatial and spectral resolution, and have revealed the temperature and abundance profiles for many systems. Markevitch et al. (1998) analyzed the spectra of 30 nearby clusters with ASCA and ROSAT, and reported that most of them showed a similar temperature decline at large radii. However, White (2000) studied a sample of 106 clusters observed with ASCA and found that 90% of the temperature profiles were consistent with being isothermal. Piffaretti et al. (2005) showed the temperature profiles of 13 nearby cooling flow clusters with XMM-Newton, and the temperature decreased by $\sim 30\%$ between 0.1 and 0.5 r_{180} using the virial radius r_{180} in good agreement with Markevitch et al. (1998) results. Recent measurements of 13 nearby relaxed clusters with Chandra by Vikhlinin et al. (2005) also indicated that the temperature reached a peak at $r \sim 0.15 r_{180}$ and then declined to about half of its peak value at $r \sim 0.5 r_{180}$.

Chandra and XMM-Newton observations also allowed detailed studies of the metal abundance in the ICM. However, these observations showed the metal abundance profiles from O to Fe only for the central region of bright

clusters or groups of galaxies dominated by cD galaxies in a reliable manner (Finoguenov et al. 2002; Fukazawa et al. 2004; Matsushita et al. 2003; Tamura et al. 2004; Matsushita et al. 2007). Abundances of O and Mg in the cluster outer regions are still poorly determined, because these satellites show relatively high intrinsic background. Because of the low and stable background and the good resolving power for emission lines below 1 keV, Suzaku XIS instrument (Koyama et al. 2007) can measure not only the precise temperature close to the virial radius of the cluster, but also abundances of O to Fe to outer regions (Sato et al. 2007a) compared with the past observations.

Clusters are also thought to grow into larger systems through complex interactions between smaller systems. It is expected that evidence of merger events can be found as non-Gaussian velocity distributions of galaxies, temperature and density inhomogeneities in the ICM, and bulk motions of the ICM. Furusho et al. (2003) found the inhomogeneous ICM as blob-like structure in the central region of AWM 7 with Chandra. Hayakawa et al. (2006) also found the inhomogeneities as the high metallicity blob in the central region of Abell 1060 with Chandra and XMM-Newton. Though Dupke & Bregman (2006) showed a large velocity gradient of $2400 \pm 1000 \text{ km s}^{-1}$ over a spatial scale of 100 kpc in the Centaurus cluster with Chandra, reconfirming their previous ASCA measurement (Dupke & Bregman 2001), Ota et al. (2007) gave a negative result of $\Delta v < 1400 \text{ km s}^{-1}$ based on measurement with Suzaku.

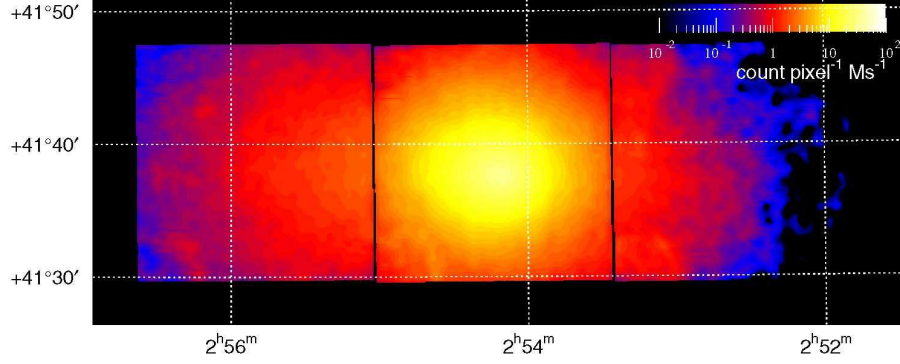


Fig. 1. Combined XIS image of the central and offset observations in the 0.5–7.0 keV energy range. The observed XIS0-3 images are added on the sky coordinate after removing each calibration source region, and smoothed with $\sigma = 16$ pixel $\simeq 17''$ Gaussian. Estimated components of extragalactic X-ray background (CXB) and instrumental background (NXB) are subtracted, and exposure are corrected, however vignetting is not corrected.

AWM 7 is a nearby cluster of galaxies ($z = 0.01724$) characterized by a smooth distribution of ICM, and has a cD galaxy NGC 1129 at the center. In the central region within $2'$, Chandra observation showed the temperature gradually dropped from 4 to 2 keV toward the cluster center, and the metal abundance rose steeply to a peak of 1.5 solar (Furusho et al. 2003). Ezawa et al. (1997) also indicated a large-scale abundance gradient of $\sim 40\%$ from center to $r \sim 500$ kpc region with ASCA. Hayakawa (2006) detected a temperature drop of $\sim 10\%$ from the central region to $r \sim 13'$ with XMM-Newton, while it had previously been considered to be flat based on ASCA observation (Furusho et al. 2001; Ezawa et al. 1997).

This paper reports results from Suzaku observations of AWM 7 out to $27' \simeq 570 h_{70}^{-1}$ kpc corresponding to $\sim 0.35 r_{180}$. We use $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_\Lambda = 1 - \Omega_M = 0.73$ in this paper. At the redshift of $z = 0.01724$, $1'$ corresponds to 21 kpc, and the virial radius, $r_{180} = 1.95 h_{100}^{-1} \sqrt{k(T)}/10$ keV Mpc (Markevitch et al. 1998), is 1.65 Mpc (79') for the average temperature of $k(T) = 3.5$ keV. Throughout this paper we adopt the Galactic hydrogen column density of $N_H = 9.83 \times 10^{20}$ cm $^{-2}$ (Dickey & Lockman 1990) in the direction of AWM 7. Unless noted otherwise, the solar abundance table is given by Anders & Grevesse (1989), and errors are 90% confidence region for a single interesting parameter.

2. Suzaku Observation and Data Reduction

2.1. Observation

Suzaku carried out three pointing observations for AWM 7 in August 2006 (PI: T. Ohashi), for the central region and 20'-east and 20'-west offset regions with exposures of 19.0, 38.5 and 39.8 ks, respectively. The observation log is shown in table 1, and the combined X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) image in 0.5–7 keV range is shown in figure 1. We analyze only the XIS data in this paper. The XIS instrument consists of four sets of X-ray CCD (XIS 0, 1, 2, and 3). XIS 1 is a back-illuminated (BI) sensor, while XIS 0, 2, and 3 are

Table 2. Estimated column density of the contaminant for each sensor at the center of CCD in unit of 10^{18} cm $^{-2}$.

	XIS0	XIS1	XIS2	XIS3
Carbon	2.53	3.97	3.83	5.79
Oxygen	0.422	0.662	0.639	0.964

Table 3. The best-fit parameters of figure 3.

	β	r_c	$S_{0.8-3 \text{ keV}}^*$
narrower	0.44 ± 0.01	$0.51' \pm 0.02'$	9.01 ± 0.28
wider	0.60 ± 0.01	$5.06' \pm 0.16'$	2.26 ± 0.08

* $S_{0.8-3 \text{ keV}}$ at the center in unit of 10^{-7} counts s $^{-1}$ arcsec $^{-2}$.

front-illuminated (FI) ones. The XIS was operated in the Normal clocking mode (8 s exposure per frame), with the standard 5×5 or 3×3 editing mode.

It is known that the optical blocking filters (OBF) of the XIS have been gradually contaminated by outgassing from the satellite. The thickness of the contaminant is different among the sensors, and is also dependent on the location on the CCD chips. The estimated column density (C/O=6 in number ratio is assumed) during the observation at the center of the CCD is listed in table 2. ¹ We included these effects in the calculation of the the Ancillary Response File (ARF) by the “xissimarfgen” Ftools task of 2006-10-26 version (Ishisaki et al. 2007). Since the energy resolution also degraded slowly after the launch due to the radiation damage, this effect was included in the Redistribution Matrix File (RMF) by the “xisrmfgen” Ftools task of 2006-10-26 version.

Table 1. Suzaku observation of AWM 7

Target name	Sequence number	Date	Exposure time	(RA, Dec) in J2000 *	After screening
AWM 7 center	801035010	2006-Aug-7	19.0 ks	(2 ^h 54 ^m 32 ^s .0, +41°35′15″)	18.9 ks
AWM 7 east	801036010	2006-Aug-5	38.5 ks	(2 ^h 56 ^m 08 ^s .4, +41°35′18″)	38.3 ks
AWM 7 west	801037010	2006-Aug-6	39.8 ks	(2 ^h 52 ^m 55 ^s .8, +41°35′16″)	39.7 ks

* Average pointing direction of the XIS, written in the RA_NOM and DEC_NOM keywords of the event FITS files.

2.2. Data Reduction

We used the version 1.2 processing data (Mitsuda et al. 2007), and the analysis was performed with HEASoft version 6.1.1 and XSPEC 11.3.2t. The analysis method was almost same as Sato et al. (2007a). However, because this observations was not supported by the Good-Time Intervals (GTI) given for excluding the telemetry saturation by the XIS team, we could not execute the process. The light curve of each sensor in the 0.3–10 keV range with 16 s time bin was also examined to reject periods of anomalous event rate greater or less than $\pm 3\sigma$ around the mean. After the above screenings, remaining exposures of the observations were almost unchanged as shown in table 1. The exposures after screening are not so different from those before screening in table 1, which represent that the non X-ray background (NXB) was almost stable during the both observations. The event screening with the cut-off rigidity (COR) was not performed in our data.

In order to subtract the NXB and the extra-galactic cosmic X-ray background (CXB), we used dark earth database of 770 ks exposure provided by the XIS team for the NXB, and employed the CXB spectrum given by Kushino et al. (2002). These analysis methods are also the same as in Sato et al. (2007a).

2.3. Generation of ARFs

Precise surface brightness profile of AWM 7 was needed to generate the Suzaku ARF, and we used the XMM-Newton image which had much better spatial resolution than Suzaku. For this XMM-Newton data, we used MOS data (32 ks) and followed the data reduction by Hayakawa (2006). We used the blank sky data as the background (Read & Ponman 2003), and eliminated point sources in the ICM. Figure 2 shows a radial profile of AWM 7 with XMM-Newton in the 0.8–3 keV range, fitted with a double- β model. The origin of the profile is placed at (RA, Dec) = (2^h54^m27^s.5, −41°34′46″) in J2000. The best-fit parameters are summarized in table 3. Though the fit is not acceptable, the temperature and abundance in the spectral fits make little influence on the ARF. Then, we generated two different ARFs for the spectrum of each region, A^U and A^B , which respectively assume the uniform sky emission and $\sim 1^\circ \times 1^\circ$ size of the double- β surface brightness profile obtained with the XMM-Newton data (table 3). We used not the raw XMM-Newton image but the smoothed surface brightness profile to generate the

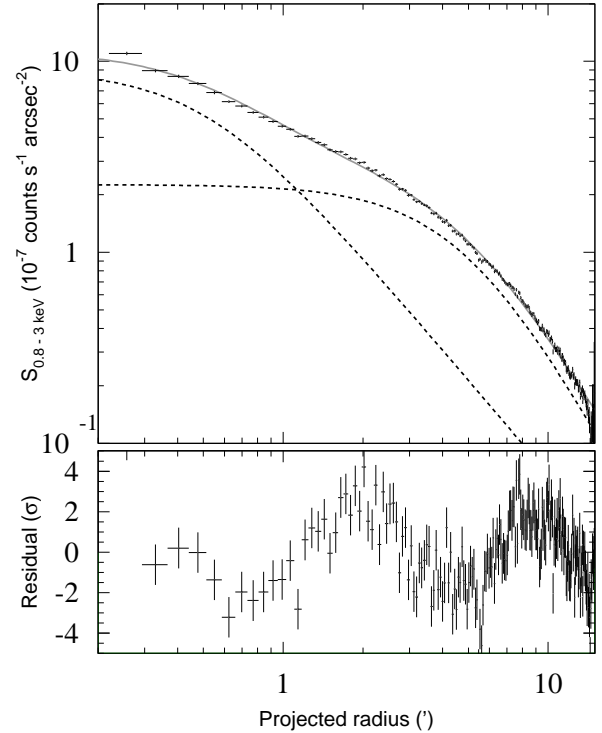


Fig. 2. In the upper panel, a radial profile of the surface brightness of AWM 7 in the 0.8–3 keV band are plotted for XMM-Newton MOS1+2 ($r < 13'$). The best-fit double- β model is shown by the solid gray line, and the two β -components are indicated by dashed lines. In the bottom panel, fit residuals are shown in unit of σ , which correspond to the data minus the folded model divided by the 1σ error of each data point.

ARFs, because the raw XMM image had the gap between the CCD chips and AWM 7 was characterized by a smooth and symmetric ICM distribution.

3. Temperature & Abundance profiles

3.1. Spectral fit

We extracted spectra from seven annular regions of 0–2', 2–4', 4–6', 6–9', 9–13', 13–17' and 17–27', centered on (RA, Dec) = (2^h54^m32^s.0, +41°35′15″). The inner four annuli were taken from the central observation, and the outer three annuli were from the two offset observations. Table 4 lists areas of the extraction regions (arcmin²), coverage of the whole annulus (%), the SOURCE_RATIO_REG

¹ Calibration database file of `ae_xiN_contami_20061024.fits` was used for the estimation of the XIS contamination ($N = 0, 1, 2, 3$ indicates the XIS sensor).

Table 4. Area, coverage of whole annulus, SOURCE_RATIO_REG and observed counts for each annular region of AWM 7.

Region *	Area [†] (arcmin ²)	Coverage [†]	SOURCE_RATIO_REG *	Counts [‡]	
				BI	FI
Center					
0–2′	12.6	100.0%	12.0%	21,800	52,737
2–4′	37.7	100.0%	19.1%	38,654	89,901
4–6′	62.8	100.0%	15.8%	33,146	75,797
6–9′	136.1	96.3%	15.2%	34,767	74,968
East					
9–13′	48.5	17.6%	2.1%	12,755	26,352
13–17′	76.3	20.2%	1.7%	14,577	31,750
17–27′	176.7	12.8%	1.6%	19,242	39,475
West					
9–13′	46.3	16.7%	2.1%	10,695	23,108
13–17′	72.7	19.3%	1.6%	11,591	23,745
17–27′	182.9	13.2%	1.7%	16,295	36,026

* The inner four annuli are extracted from the central observation, and the outer annuli are from the east and west observation, respectively.

[†] The largest values among four sensors are presented.

[‡] Observed counts including NXB and CXB in 0.4–7.1 keV for BI and 0.4–8.1 keV for FI.

values² and the observed counts in the range 0.4–8.1 keV including NXB and CXB for the BI and FI sensors.

The annular spectra are shown in figure 3. Emission lines from Mg, Si, S, Fe are clearly seen in the spectrum for each ring. The O VII and O VIII lines are prominent in the outer rings, however, most of the O VII emission is considered to come from the local Galactic emission.

The basic strategy for the spectral fit is described in subsection 4.2 of Sato et al. (2007a). The spectra for the east and west regions were fitted simultaneously according to the distance from the cluster center. The fit parameters were linked except for the normalization. We will examine the difference between the east and west regions in section 3.4. The BI and FI spectra were also fitted simultaneously in the 0.4–8.1 keV band excluding the response anomaly around Si K-edge (1.825–1.840 keV). In the simultaneous fit, only the normalization were allowed to take different values between BI and FI data, though the derived normalizations were quite consistent between the two.

3.2. Estimation of Galactic Component

It is important to estimate the foreground Galactic emission precisely, for which the offset observations of AWM 7 give useful data. The Galactic component is prominent in the 17–27′ annulus as shown in figure 3, however the ICM component is still dominant in almost all the energy range except for the O VII line. We also

dealt with these data in the same way as in Sato et al. (2007a). We performed simultaneous fit in the whole 0.4–8.1 keV range (except for 1.825–1.840 keV) for the spectra in 13–17′ annulus of the west offset region and the one in 17–27′ annuli of the east and west offset regions. We assumed either one or two temperature *apec* model for the Galactic component, and the fit results are presented in table 5. The resultant normalizations of the *apec* models in table 5 are scaled so that they give the surface brightness per arcmin².

We examined the improvement of χ^2 ($\Delta\chi^2 = 38$) values with the *F*-test, and addition of the *apec*₂ component was necessary with high significance (error probability $\sim 10^{-7}$). We further allowed the normalization of the *apec*₂ to be free for those three annuli. We concluded that the two *apec* models are required to account for the Galactic component. Hereafter, the model *apec*₁ + *apec*₂ + *phabs* × *vapex* is used for the spectral fits, unless otherwise stated.

In order to take into account both the existence of the Galactic component itself and the propagation of its statistical error, we fitted the spectrum in each individual annulus simultaneously with the one in the outermost annulus, i.e. at 17–27′ in the east and west offset regions. The normalization for the sum of the *apec*₁ and *apec*₂ components was constrained to give the same surface brightness in all annuli, and the temperatures of these two *apec* models were also common for all the regions including the 17–27′ annuli. These common normalizations, *Norm*₁ and *Norm*₂, and the common temperatures, *kT*₁ and *kT*₂, were the free parameters. The derived normalizations and temperatures for the Galactic components are consistent with the values already shown in table 5(b) within their errors. Influence on the ICM temperature and abundance due to the modeling of the Galactic component will be examined in subsection 3.3.

3.3. Radial Temperature & Abundance Profiles

The fits are not acceptable due mainly to the very high photon statistics compared with systematic errors in the instrumental response. However, these results are useful to assess how effectively the metal abundances are constrained. We fitted the spectra with all the metal abundances as free parameters. Somehow, Ne and Ni abundances turn out to be higher than the other elements. This might be because the lines from these elements are not well resolved from the Fe-L line complex. We tentatively left these Ne and Ni abundances vary freely in the spectral fit.

The resultant radial profiles of temperature and abundance are shown in figure 4. The temperature profile shows a mild cooling core in the central region ($r \lesssim 6'$), and declines from ~ 3.8 keV at 6–9′ region (~ 130 kpc) to ~ 3.4 keV in the outermost annulus of 17–27′ (~ 360 – 570 kpc ~ 0.22 – $0.35 r_{180}$). Abundance profiles of O, Mg, Si, S, and Fe are obtained up to a radius of $27' \simeq 570$ kpc. Abundances of Mg, Si, S, and Fe all decline with radius from ~ 1.5 , 1.1, 1.1 and 0.9 solar in the central region, to ~ 0.9 , 0.4, 0.3 and 0.4 solar, respectively, in the clus-

² SOURCE_RATIO_REG represents flux ratio in the assumed spatial distribution on the sky (double- β model) inside the accumulation region to the entire model, and written in the header keyword of the calculated ARF by “xissimarfgen”.

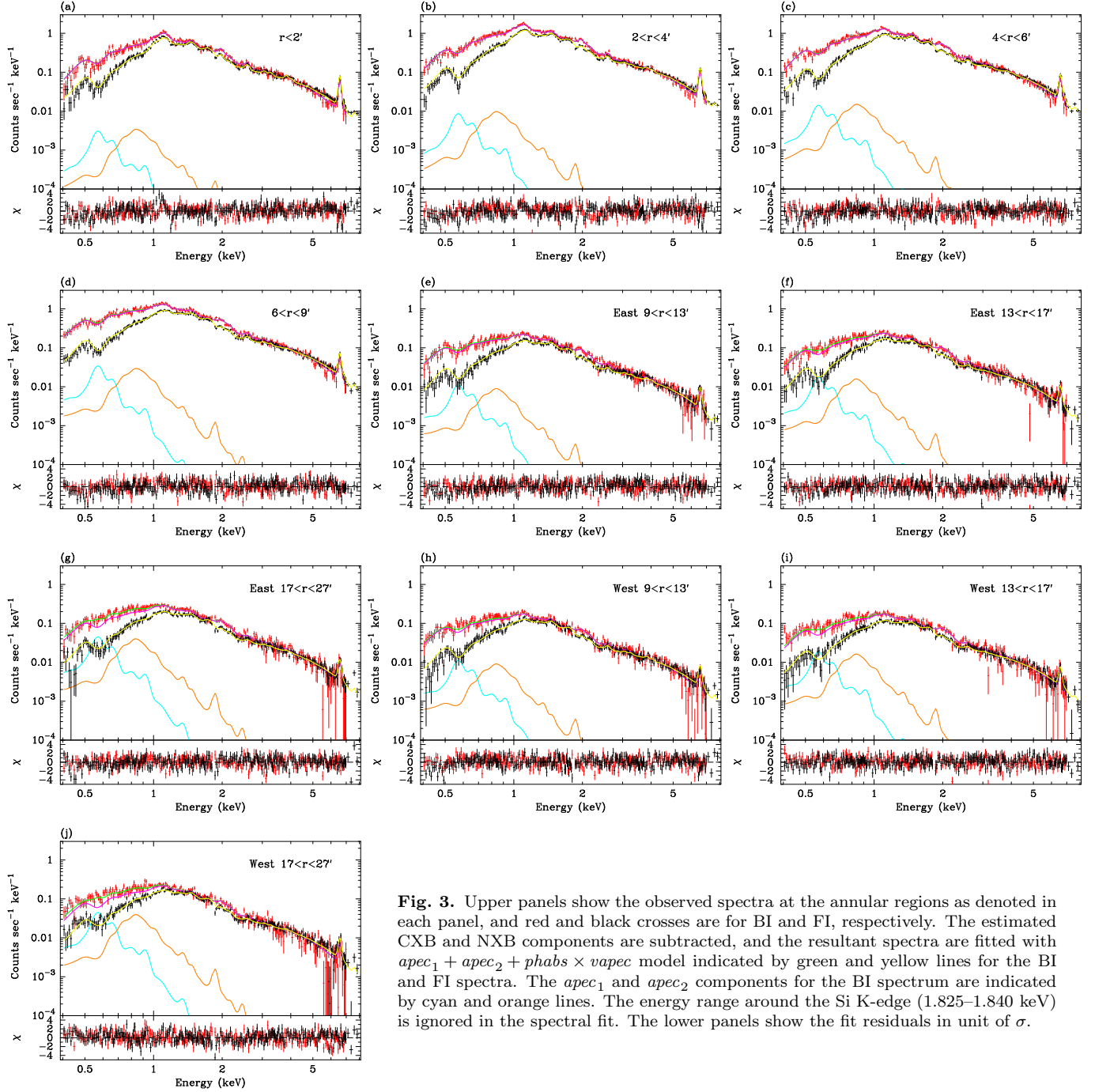


Fig. 3. Upper panels show the observed spectra at the annular regions as denoted in each panel, and red and black crosses are for BI and FI, respectively. The estimated CXB and NXB components are subtracted, and the resultant spectra are fitted with $apec_1 + apec_2 + phabs \times vapec$ model indicated by green and yellow lines for the BI and FI spectra. The $apec_1$ and $apec_2$ components for the BI spectrum are indicated by cyan and orange lines. The energy range around the Si K-edge (1.825–1.840 keV) is ignored in the spectral fit. The lower panels show the fit residuals in unit of σ .

Table 5. The best-fit parameters of the $apec$ component(s) for the simultaneous fit of the spectra in 13–17' and 17–27' annuli of the west offset region and in 17–27' annulus of the east offset region.

Fit model	$Norm_1^*$	kT_1 (keV)	$Norm_2^*$	kT_2 (keV)	χ^2/dof
(a) $apec_1 + phabs \times vapec$	7.52 ± 0.70	$0.262^{+0.035}_{-0.013}$	—	—	1781/1495
(b) $apec_1 + apec_2 + phabs \times vapec$	6.59 ± 0.46	$0.157^{+0.041}_{-0.035}$	0.32 ± 0.07	$0.612^{+0.052}_{-0.055}$	1743/1493

* Normalization of the $apec$ component divided by the solid angle, Ω^u , assumed in the uniform-sky ARF calculation (20' radius), $Norm = \int n_e n_H dV / (4\pi(1+z)^2 D_A^2) / \Omega^u \times 10^{-20} \text{ cm}^{-5} \text{ arcmin}^{-2}$, where D_A is the angular distance to the source.

Table 6. Summary of the best-fit parameters of the *vapec* component for each annular region of AWM 7. with the *apec*₁ + *apec*₂ + *phabs* × *vapec* model*.

Region	$Norm^\dagger$	kT (keV)	O (solar)	Ne (solar)	Mg (solar)	Si (solar)	S (solar)	Fe (solar)	Ni (solar)	χ^2/dof
0–2'	1007 ± 36	$3.41^{+0.04}_{-0.04}$	$0.62^{+0.34}_{-0.31}$	$2.11^{+0.40}_{-0.37}$	$1.50^{+0.32}_{-0.31}$	$1.13^{+0.18}_{-0.17}$	$1.08^{+0.20}_{-0.20}$	$0.87^{+0.05}_{-0.04}$	$1.71^{+0.61}_{-0.58}$	1872/1493
2–4'	595 ± 16	$3.66^{+0.04}_{-0.04}$	$0.57^{+0.26}_{-0.25}$	$1.65^{+0.28}_{-0.27}$	$1.18^{+0.24}_{-0.24}$	$0.94^{+0.13}_{-0.13}$	$0.85^{+0.16}_{-0.15}$	$0.73^{+0.03}_{-0.03}$	$1.47^{+0.47}_{-0.46}$	1899/1493
4–6'	342 ± 10	$3.78^{+0.05}_{-0.05}$	$0.49^{+0.28}_{-0.26}$	$1.38^{+0.29}_{-0.28}$	$1.20^{+0.27}_{-0.27}$	$0.54^{+0.14}_{-0.14}$	$0.67^{+0.17}_{-0.17}$	$0.56^{+0.03}_{-0.03}$	$0.56^{+0.53}_{-0.52}$	1805/1493
6–9'	182 ± 5	$3.82^{+0.06}_{-0.06}$	$0.63^{+0.25}_{-0.27}$	$1.33^{+0.28}_{-0.29}$	$1.05^{+0.26}_{-0.27}$	$0.57^{+0.14}_{-0.15}$	$0.74^{+0.18}_{-0.18}$	$0.50^{+0.03}_{-0.03}$	$2.11^{+0.57}_{-0.56}$	1816/1493
9–13'	113 ± 4	$3.62^{+0.08}_{-0.08}$	$0.39^{+0.33}_{-0.34}$	$1.08^{+0.33}_{-0.32}$	$1.32^{+0.32}_{-0.33}$	$0.53^{+0.17}_{-0.17}$	$0.62^{+0.21}_{-0.21}$	$0.41^{+0.04}_{-0.04}$	$2.33^{+0.70}_{-0.68}$	2361/2014
13–17'	72 ± 2	$3.58^{+0.08}_{-0.08}$	$0.10^{+0.37}_{-0.10}$	$0.86^{+0.30}_{-0.31}$	$0.75^{+0.29}_{-0.28}$	$0.50^{+0.16}_{-0.15}$	$0.38^{+0.19}_{-0.18}$	$0.32^{+0.03}_{-0.03}$	$1.22^{+0.64}_{-0.61}$	2370/2014
17–27'	29 ± 1	$3.34^{+0.07}_{-0.07}$	$0.46^{+0.57}_{-0.46}$	$0.91^{+0.32}_{-0.31}$	$0.88^{+0.29}_{-0.27}$	$0.42^{+0.15}_{-0.14}$	$0.29^{+0.17}_{-0.17}$	$0.36^{+0.04}_{-0.04}$	$1.88^{+0.64}_{-0.60}$	— [‡]

* Spectrum in each annulus was simultaneously fitted with the outermost 17–27' spectrum obtained by the two offset observations. Errors show 90% confidence statistical error range, without including systematic errors. These results are shown in figure 4, where Ne and Ni abundances may have large systematic uncertainties because XIS cannot resolve the ionized Ne lines from the Fe-L line complex.

[†] Normalization of the *vapec* component scaled with a factor of $SOURCE_RATIO_REG / AREA$ in table 4,

$Norm = \frac{SOURCE_RATIO_REG}{AREA} \int n_e n_H dV / (4\pi (1+z)^2 D_A^2) \times 10^{-20} \text{ cm}^{-5} \text{ arcmin}^{-2}$, where D_A is the angular distance to the source. For the offset regions, these are the values of normalization of the east region.

[‡] The 17–27' annulus of the east and west offset regions were fitted simultaneously with other annuli, and the best-fit values with the 13–17' annulus of the east and west offset regions, respectively, are presented here.

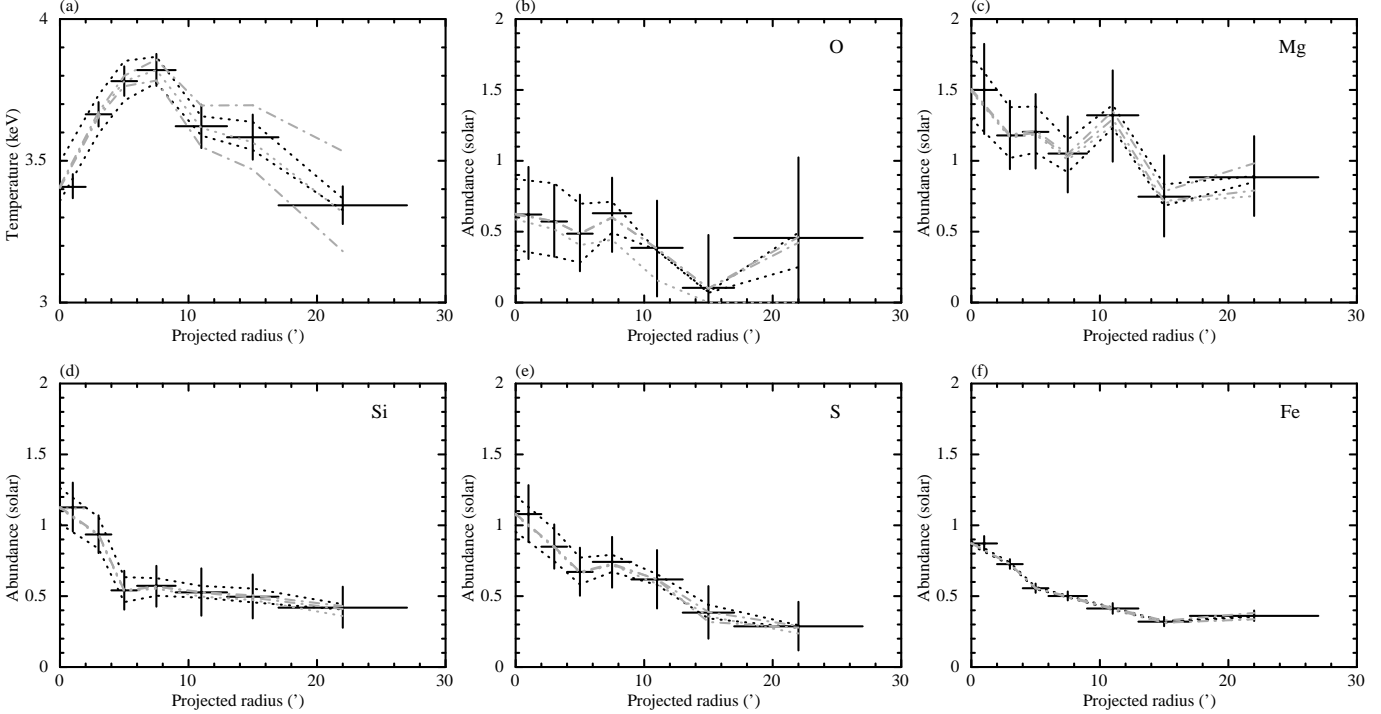
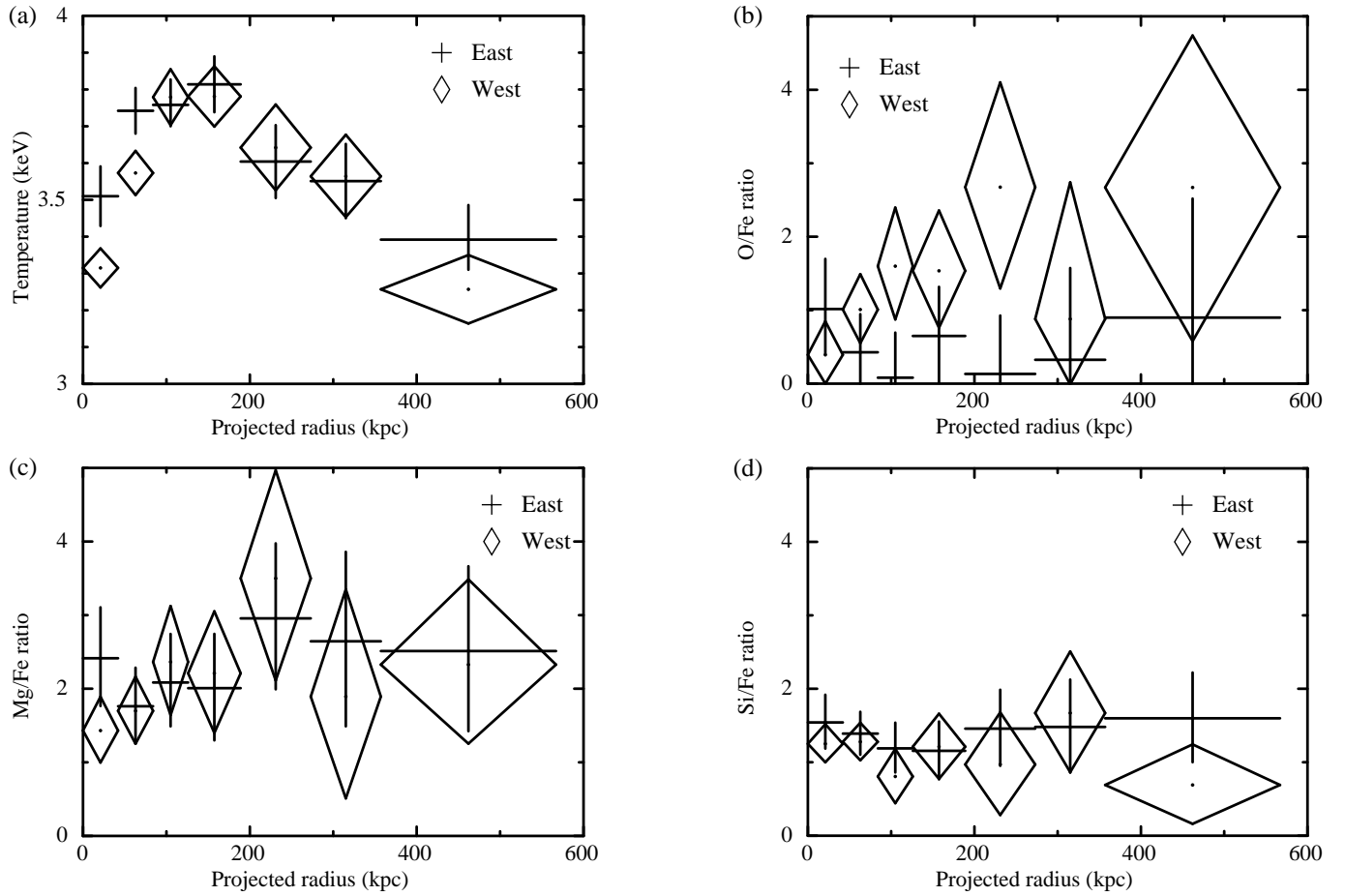


Fig. 4. (a) Radial temperature profiles derived from the spectral fit for each annulus. The horizontal axis denotes the projected radius. Black dotted lines indicate shifts of the best-fit values by changing thickness of the OBF contaminant by $\pm 10\%$. Light-gray dotted lines denote those when the estimated CXB and NXB levels are changed by $\pm 10\%$. Light-gray dash-dotted line shows the best-fit value when the Galactic component is modeled by a single temperature *apec* model. (b)–(f) Radial abundance profiles derived and plotted in the same way as in (a).

Table 7. List of χ^2/dof for each fit of AWM 7.

Region	nominal	contaminant		background	
		+10%	-10%	+10%	-10%
center					
0–2'	1872/1493	1829/1493	1939/1493	1909/1493	1871/1493
2–4'	1899/1493	1876/1493	1965/1493	1937/1493	1897/1493
4–6'	1805/1493	1789/1493	1849/1493	1844/1493	1803/1493
6–9'	1816/1493	1786/1493	1852/1493	1858/1493	1814/1493
East & West					
9–13'	2361/2014	2337/2014	2395/2014	2408/2014	2355/2014
13–17'	2370/2014	2365/2014	2390/2014	2424/2014	2362/2014

**Fig. 5.** (a) Radial temperature profile along the east-west direction. (b)–(d) Radial O, Mg, and Si to Fe abundance ratios along with the east and west directions same as (a).

ter outskirts. The O abundance shows somewhat flatter radial distribution.

Additional uncertainties on the derived parameters due to the OBF contaminant and the background (CXB + NXB) systematics are shown in table 6 and figure 4. Here, we fitted the spectra again by changing the background normalization by $\pm 10\%$, and the range of parameters are plotted with light-gray dotted lines in figure 4. Systematic error in the background estimation is almost negligible. Change of the best-fit parameters by using alternative modeling of the Galactic component with a single temperature *apec* model was investigated, and the results are indicated with light-gray dash-dotted lines. The differences are within the statistical error for the inner five annuli. However, O abundance becomes lower than the 90% confidence error range at the outer two annuli, and temperature and Fe abundance become lower at the outermost annulus. This is due mainly to the fact that the XIS cannot resolve the ICM O VIII line from the Galactic one by the redshift. The systematic error range due to the uncertainty in the OBF contaminant is indicated by black dotted lines. A list of χ^2/dof is presented in table 7.

3.4. Difference Between East and West Regions

We examined the difference in the temperature and abundance profiles between the east and west directions from the cluster center. We treated the spectra in the east and west regions separately, but they were always fitted jointly with the outermost spectrum in 17–27' where the east and west data were combined together in the same way as described in 3.2. Figure 5(a) shows the temperature profiles along the east-west direction of the cluster. The west direction shows slightly steeper temperature gradient than the east direction. Figure 5(b)–(d) also show the abundance ratios of O, Mg, Si divided by Fe in order to look into relative variation in the abundance profiles. While Si/Fe ratio is consistent to be a constant value along the east-west direction, Mg/Fe ratio looks an increase with radius in both the directions. Though O/Fe ratio has a large uncertainty, the west direction shows larger values than the east.

4. Bulk Motions in the ICM

4.1. Spectral Analysis in Search of Bulk Motions

In order to search for possible bulk motions of the ICM, the central energy of He-like Fe-K line (the rest-frame energy of 6.679 keV) was examined to look into a positional variation. We divided the $18' \times 18'$ square XIS field of view into smaller cells. The central observation was divided into 16 times $2.2' \times 2.2'$ cells, 12 times $4.5' \times 4.5'$ cells as shown in figure 6(a). For the east and west offset regions, we divided each field into 6 times $4.5' \times 8.9'$, 3 times $8.9' \times 8.9'$ and one $17.8' \times 8.9'$ cells. We co-added the data from only the FI sensors (XIS0, 2 and 3). For the accurate determination of the iron-line energy, we fitted the background-subtracted XIS (FI) spectra with a simple model over the 5–10 keV energy range. The model we used consists of a continuum represented by a *power-*

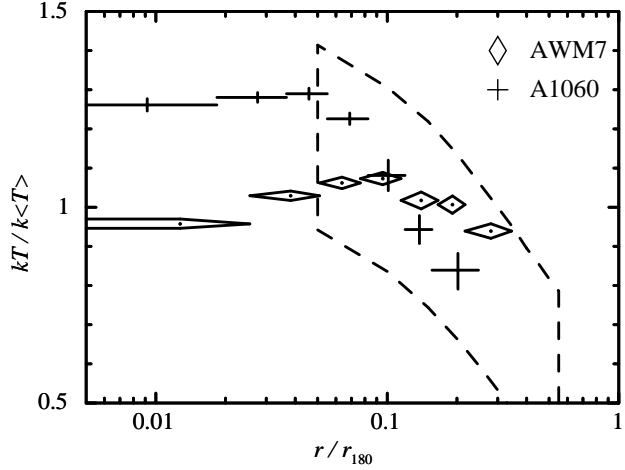


Fig. 7. Scaled temperature profiles using normalized temperatures and the radius scaled by the virial radius. The A 1060 data are taken from Sato et al. (2007a). The region indicated by dashed line shows result of ASCA observations by Markevitch et al. (1998).

law model and Gaussian profiles as described in Ota et al. (2007), and we determined the central energy of He-like Fe-K α line. In the fit, we fixed the intrinsic width of the Gaussian line to be 0. We employed the central energies of He-like Fe-K α and H-like Fe-K α lines at the rest frame to be 6.679 and 6.964 keV, respectively, which are expected from an *apec* model with $kT = 3.5$ keV.

4.2. Constraint on the Existence of Bulk Motions

Distribution of the line central energy are shown as a color coded map in figure 6(b) and against the cell number in figure 6(c), with 90% confidence statistical errors. The dot-dashed line in figure 6(c) corresponds to the redshifted central energy at AWM 7 of $E_{cl} = 6.566$ keV with $z = 0.01724$, based on the rest-frame central energy $E_0 = 6.679$ keV. The dotted lines show the range of current calibration error of $z = 0.003$ or ~ 20 eV. Figure 6(b) and (c) indicate no significant systematic feature for the gas motion within the 90% confidence level.

Since there seem to be some hint of difference between the east and west regions in the central observation, we looked into a larger structure. Spectra in the cell numbers of 6–19, or 20–33 were summed up to evaluate the east or west difference for the central pointing, respectively. The results for the east and west regions correspond to the left and right open circles in figure 6(c). The difference was 15 ± 6 eV between the east and west regions with the 90% confidence error. However, it is known that the central energy of a line shows dependence on the read-out direction of XIS chip, and the systematic uncertainty is about ~ 20 eV. We therefore conclude that the upper limit for the bulk motion of the gas to be $\Delta E \lesssim 40$ ($15 \pm 6 \pm 20$) eV based on the measurement of the central energy of He-like Fe-K α line, which corresponds to $\Delta v \lesssim 2000$ km s $^{-1}$.

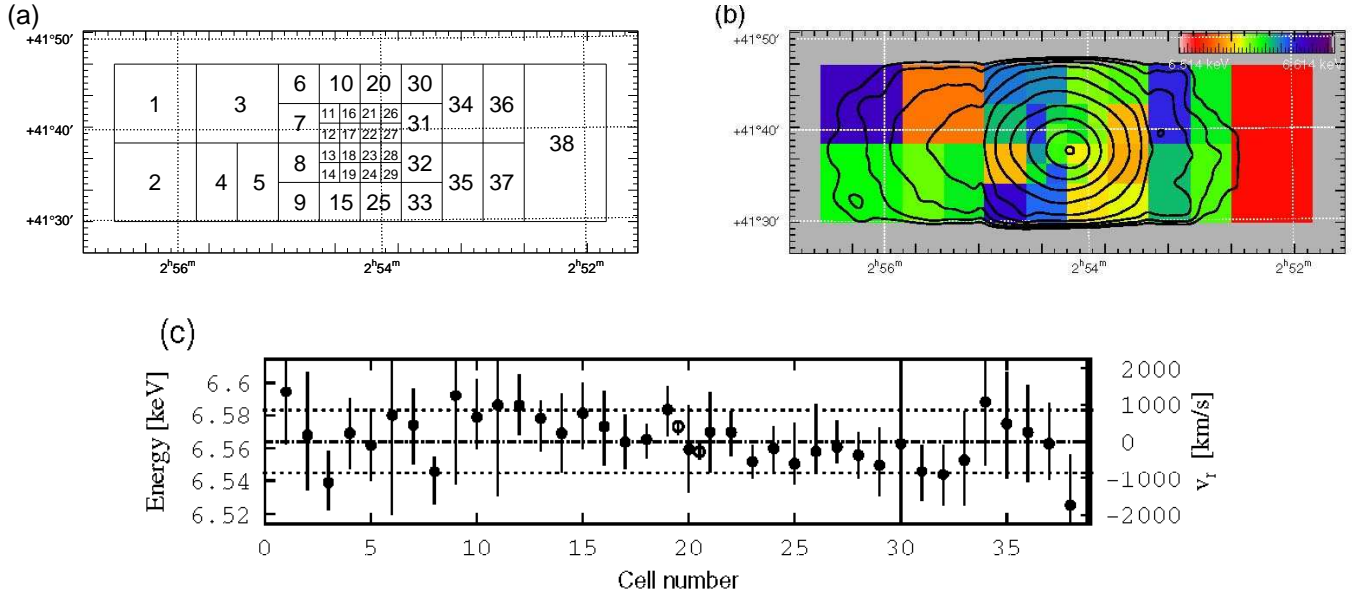


Fig. 6. Measurement of bulk motion using the central energy of He-like Fe-K lines. (a) Spatial division and the position numbers. Depending of the brightness, the whole observed region is divided into $2.2' \times 2.2'$ (16 cells) or $4.5' \times 4.5'$ (12 cells) regions for the central observation, and into $4.5' \times 8.9'$ (6 cells), $8.9' \times 8.9'$ (3 cells), and $17.8' \times 8.9'$ (1 cell) regions for the offset observations. (b) Color representation of the spatial distribution of the central energy of redshifted iron line for each cell. The map is overlaid on the contour in figure 1. (c) The energy of He-like Fe-K line against the cell numbers. The energy of redshifted He-like Fe-K α line at AWM 7 ($z = 0.01724$) is 6.566 keV. The dot-dashed line corresponds to the cluster redshift, and the dotted lines indicate calibration error range ($z = 0.003$ or ~ 20 eV) of XIS. Open circles indicate the average for the east or west region in the central pointing.

5. Discussion

5.1. Temperature Profile

Suzaku observation showed the temperature profile of AWM 7 to $\sim 0.3r_{180}$ region of the cluster, extending the previous Chandra and XMM-Newton measurements. Hayakawa (2006) showed the temperature in AWM 7 to drop from 3.8 keV at the peak to 3.5 keV at $r \sim 13'$ with XMM-Newton, and the present study confirmed their results in a wider range of radius. Previous ASCA observation of AWM 7 indicated fairly uniform temperature distribution in the whole cluster region (Furusho et al. 2001; Ezawa et al. 1997), however their results are consistent with ours within the error because the temperature drop is quite small that it could well be regarded as isothermal in observation with lower statistics.

To compare the temperature profile with those in other clusters, we normalized temperature with the emission-weighted average of $k\langle T \rangle = 3.56$ keV for AWM7, and plotted it against the radius normalized with the viral radius in figure 7. We calculated the $k\langle T \rangle$ in the range of 0.1 – $0.3r_{180}$ with Suzaku. The normalized temperature profile is compared with Abell 1060, which shows $k\langle T \rangle = 2.49$ keV in 0.1 – $0.25r_{180}$ (Sato et al. 2007a). Note that AWM 7 has a cD galaxy at the center, while Abell 1060 does not. The temperature gradient of AWM 7 is clearly less steep than that of Abell 1060, while these profiles are both consistent with the broad range (dashed line region in figure 7) given by Markevitch et al. (1998) with ASCA. The Markevitch et al. (1998) result is consistent with the temperature gradients for several clusters studied by Vikhlinin

et al. (2005) with Chandra and Piffaretti et al. (2005) with XMM-Newton.

Hayakawa (2006) showed a systematic difference with XMM-Newton in the temperature gradients between 9 cD and 13 non-cD clusters, including both AWM 7 and Abell 1060. They showed that both cD and non-cD clusters show consistent gradients for a radius range $0.05 < r/r_{180} < 0.55$, with general agreement with the Markevitch et al. (1998) result with slightly higher absolute temperatures. They, however, found that, in $r/r_{180} < 0.05$, temperatures of the cD clusters showed a systematic drop toward the center, and this feature was not clearly recognized in the non-cD clusters. Such a feature in the central region is also seen in our observation of AWM 7.

5.2. Abundance Profiles

The good XIS sensitivity to emission lines, especially below 1 keV, enabled us to measure O and Mg abundances out to $\sim 0.35r_{180}$ with Suzaku. The radial abundance profiles of Si, S, and Fe show steeper drop than those of O and Mg. Ezawa et al. (1997) reported a large-scale abundance gradient from 0.5 solar at the center to $\lesssim 0.2$ solar in the region over 500 kpc ($H_0 = 50$ km s $^{-1}$ Mpc $^{-1}$), consistent with our result for Fe. On the other hand, abundance determination of Ni and Ne has a problem because of possible confusion with strong Fe-L lines. Also, we have to note that the O abundance in the outer region of our observation is strongly affected by the foreground Galactic emission as described in subsection 3.2. Even allowing the O distribution to be a rather preliminary result, the combined Mg and O feature suggests that their distribu-

tion is likely to be more extended than those of Fe and Si. This is at least consistent with the view that the metals injected from Type II supernova, i.e. O and Mg, in the early phase of galaxy formation in the wind form show extended distribution (Arimoto & Yoshii 1987). In contrast, the steep gradient of Fe and Si distribution suggests they are mostly produced by Type Ia supernova in a later stage, with enhanced contribution from the cD galaxy as shown by De Grandi et al. (2004).

We calculated cumulative metal mass profiles by combining the present abundance results with X-ray gas mass profile with XMM-Newton. Since measured metals have different yields from the two types of supernova, with O and Mg mostly synthesized by type II supernovae (SNe II) while type Ia supernovae (SNe Ia) giving large yields of Si, S and Fe, we can estimate their relative contributions which can best account for the measured abundance pattern. We thus estimated the number ratio of SNe II to SNe Ia to be ~ 4 in the ICM of AWM 7 as reported in Sato et al. (2007b). We also calculated radial mass-to-light ratios for O, Mg, and Fe, and compared the values with those in other systems. As a result, it is suggested that smaller systems with lower gas temperature tend to show lower mass-to-light ratios for O, Mg, and Fe as shown in Sato et al. (2007c).

5.3. Morphology of AWM 7

No significant bulk motion of the gas exceeding the sound speed, $\sim 1000 \text{ km s}^{-1}$, was detected in the ICM of AWM 7, even though the X-ray image of AWM 7 is highly elongated in the east-west direction. Neumann & Boehringer (1995) and Furusho et al. (2001) reported the major to minor axis ratio to be 0.8. This elongation is fairly parallel to the large-scale filament of the Pisces-Perseus supercluster, which runs almost along the east-west direction. We will consider possible processes to explain this elongation. In general, the simplest explanation for the deviation from the spherical symmetric shape is that the cluster is rotating. However, X-ray spectra show no indication of significant rotation at present. Furthermore, based on the standard CDM scenario, it is difficult to make a cluster to have a large angular momentum (? , e.g.)]peebles69,white84,barnes87. Tidal interaction with the Perseus cluster is another possible process, however Neumann & Boehringer (1995) showed that the tidal effect of Perseus cluster was too small to cause the observed large ellipticity of AWM 7.

Another possible process is asymmetric accretion of matter (? , see e.g.)]neumann95. Directional mass accretion may lead to an ellipsoidal or triaxial dark matter halo. If the intra-cluster gas is in hydrostatic equilibrium in the gravitational potential dominated by the dark matter, gas distribution should deviate from the spherical symmetry. If we can obtain more detailed information about the profile of the eccentricity of the gas isodensity surface as well as precise density and temperature profiles, we can reconstruct the three-dimensional dark matter structure (? , e.g.)]lee04. This will give us an important knowledge of the dark matter relaxation process.

Finally, if the gas infalls in an asymmetric manner from the filament onto the relaxed cluster and the accreted gas has not been mixed with the original intra-cluster gas, the gas profile deviates from spherical symmetry and X-ray morphology becomes elliptical. In this case, the gas in the outer part of the east and west regions may keep the physical properties such as metal abundance when the gas was in the filament. The warm gas in the large-scale filament is an important part of the warm-hot intergalactic medium (WHIM) which is the dominant component of baryons in the local universe (? , e.g.)]yoshikawa03. Several missions are proposed to detect WHIM through O VII and O VIII emission lines (? , e.g.)]ishisaki04,ohashi06,piro06,denherder06. If metal abundance of gas in filaments is as high as that of ICM, the detection of WHIM becomes relatively easy and the missing baryon problem can be answered in the near future. Furthermore, we need to revisit the metal production and ejection processes closely to explain the high metal abundance in the intergalactic gas. To confirm such a possibility, deeper X-ray observation in the outermost region of AWM 7 is important.

Part of this work was financially supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan, Grant-in-Aid for Scientific Research No. 14079103, 15340088, 15001002, 16340077, 18740011.

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